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Exploratory flight tests of advanced piloted spacecraft concepts

ORAL VERSION

EXPLORATORY FLIGHT TESTS OF ADVANCED PILOTED SPACECRAFT CONCEPTS

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INTRODUCTION

In an effort to reverse the trends toward complexity of design and operation of advanced manned research vehicles, simplified approaches and concepts have been utilized in two recent exploratory flight test programs at the NASA Flight Research Center. These programs involved design, construction, and operational flight research tests of the paraglider research vehicle, or Paresev, and the lifting-body vehicle, or M-2. Both programs were initiated as a result of interest shown throughout NASA, industry, and the military. These configurations were being considered for use in manned operational systems, and, even though they had undergone extensive wind-tunnel and model testing, it was felt that a piloted vehicle should be flown to answer questions on their capability to maneuver, flare, and land.

To obtain both qualitative and quantitative results on these methods in the shortest time and at a minimum cost, vehicle design was kept simple. The results of the tunnel tests on these configurations served as a basis for the design. Of primary concern during design was weight, from both the operational and safety aspects. From the operational standpoint, because both vehicles are unpowered and towed aloft for free-flight gliding, tow-vehicle power and velocity requirements are considerably reduced with a lightweight craft. Thus, it was possible to make the initial flights with a ground-tow vehicle. Also, from the safety aspect, vehicle damage and personnel injury are minimized in the event of an accident.

To design and construct the Paresev and the M-2 aircraft, project groups were formed consisting of engineers, craftsmen, and technicians. The group leaders were responsible to the Center Director. This project orientation visibly reduced the red tape involved in such a program and expedited construction and reduced program costs.

This paper discusses the program philosophy, design, flight testing, and data-acquisition techniques and presents some of the results obtained from the Paresev and M-2 programs.

VEHICLE DESCRIPTION

The lightweight-vehicle approach was chosen because it offers many advantages, such as minimum cost, simple design, manual control system, and ease of maintenance, modification, and repair. Towed-vehicle operation was selected in preference to onboard propulsion. This again simplified vehicle design and construction and eliminated undesirable power effects on vehicle stability and control. It also greatly reduced the initial vehicle costs. The actual construction was accomplished in-house with only one or two components per vehicle being contracted for. This procedure allowed the design engineers to utilize simple drawings and sketches during the fabrication and to observe the construction and make any necessary changes or modifications as the work progressed.

In lieu of a thorough stress analysis, both craft were subjected to severe proof testing. For instance, drop tests from a 42-inch height were made to demonstrate structural integrity at a 15-foot-per-second vertical velocity, 6g landing. The lifting body was further proof-tested to design dynamic pressure during the course of a wind-tunnel program in the Ames' full-scale tunnel prior to the initial flight.

One of the problems during design and construction was that of keeping the designers from "over-engineering" components and making them too complex. By keeping things simple, it was possible to make control and configuration changes overnight and, in many instances, within minutes.

Paresev

The original Paresev, shown in figure 1 and designated vehicle A, was badly damaged during checkout of a new pilot. The parts that were usable were rebuilt in the configuration, as shown in figure 2. This configuration was designated vehicle B. Major differences between the two craft are presented in figure 3.

The fuselages of both vehicles were fabricated of steel tubing and were of the open-framework type. The keel and leading edges of the wings were constructed of 2 1/2-inch-diameter aluminum tubing. The boom sweep angle was held constant at 50° by the use of a rigid spreader bar. Additional wing structure fabricated of steel tubing assured structural integrity. Where possible, off-the-shelf hardware was used to decrease fabrication time. For instance, the shock absorbers on vehicle B are Ford automotive, the wing universal joint is a 1948 Pontiac, and the tires and wheels are Cessna 175 type.

A sailmaker was contracted to sew the wing according to our planform. After we designed the first membrane--attaching methods, material, etc.--and made the first flights with this wing, we decided that his advice should have been heeded since there was considerable flutter and bulging of the membrane. We then told him to sew a wing as he desired and, using sailing techniques, he produced one with excellent contours. He is now manufacturing the wing membranes for the Gemini paraglider.

Because the Paresev control was by the direct manual center-of-gravity shift method, the control forces were determined by the relationship of the wing center of pressure and the wing pivot-point and control-system gearing. Center-of-pressure position of the wing was assumed to be at a 46-percent-keel location based on wind-tunnel results; however, extremely high forces were encountered at this pivot point. Trial-and-error relocation of the wing reduced the control forces to acceptable levels over a speed range of 30 KIAS to 65 KIAS.

The Paresev had the same wing loading and lift-drag ratio that the Gemini paraglider will have; however, the Paresev fuselage is rigidly supported, whereas the Gemini fuselage will be supported by cables.

Lifting Body

A three-view drawing and pertinent physical characteristics of the M-2 are shown in figure 4.

Figure 5 is a photograph of the M-2 hull assembly. Because of inexperience in wood construction and with our experience with the Paresev wing in mind, we thought it best to contract the hull assembly to a glider manufacturer. Typical wooden glider construction was used with 3/32-inch mahogany plywood skin and 1/8-inch mahogany rib sections reinforced with spruce. The exterior was wrapped with Dacron and doped for a more durable surface.

Figure 6 shows the internal structure and landing-gear assembly. The internal or primary structure is welded steel tubing. This assembly includes the controls (stick and rudder pedals) and control system up to a mixer plate. The nose-gear is a slightly modified Cessna 150 gear; the main-wheel assemblies are Cessna 150 units; the main-gear shock and strut units are our design and incorporated a viscous damper and bungee combination. As a matter of interest, the damper consists of a cylinder with a sloppy piston and 50-weight motor oil. By drop tests and varying the viscosity of the oil, we attained the desired degree of damping. The seat shown in the photo has been replaced with a modified T-37 rocket-ejection seat that weighs 100 pounds, including the parachute.

Figure 7 is a photograph of the assembled vehicle. The vertical fins, rudders, and elevons are thick slab sections, constructed of 0.016 aluminum sheet. The trailing-edge flaps are welded 0.028 aluminum tube, covered with Dacron. The canopy is a modified glider canopy of molded Plexiglas and plywood and closes the access hole provided for removal of the internal structure. The nose and side windows are Plexiglas and are oriented to provide additional visibility prior to touchdown. The tow hook is located on the nose-gear strut just below the hull.

Because of the low lift-drag ratio indicated by full-scale tunnel tests and the questionable visibility available, some means of giving the pilot more time during flare in an emergency condition was considered essential. Vehicle propulsion was the simplest way. A survey of off-the-shelf small rockets and JATO units was made. Most of these were not immediately available or were priced out of range. A small, solid-propellant batch test motor was suggested by the Naval Ordnance Test Station at China Lake. This rocket was modified slightly, qualified, and delivered. The rocket provides 230 to 250 pounds of thrust for 10 seconds.

In order to confirm the results of scale model testing and to evaluate the effects of real hardware on performance, the flight vehicle was tested in the 40- by 80-foot wind tunnel at Ames Research Center (fig. 8). To expedite the tunnel tests, a pilot or engineer was inside the M-2 to position the controls. This allowed a data point to be taken on the average of once every minute. At one time, we ran the tunnel 7 hours without shutting down.

The control-system arrangement for the M-2 is conventional, and the stick-to-surface ratios were selected on the basis of simulator and full-scale-tunnel results. The longitudinal control surfaces consist of the trailing-edge flaps and the outer elevons. Roll control is through differential elevon with directional control through the rudders. Longitudinal forces were reduced from a constant 28 pounds pull to 8 to 10 pounds by a fixed tab on the flaps. Rudder and elevon forces were nil and resulted in bungee being placed in the system for feel.

FLIGHT OPERATIONS

The flight program for both vehicles began with ground tow tests. Several tows were made before lift-off was attempted to check the control rigging and to familiarize the pilot with the vehicle's ground stability. As the pilot's confidence and experience increased, tow speeds were also increased until lift-off was attained. With the Paresev, lift-off was about 40 KIAS; with the M-2, about 75 KIAS. The entire speed range of the Paresev was covered during ground tows. Maximum ground tow speed with the M-2 was 104 knots or about 95 percent of its velocity envelope. During these tests, a drag link was placed in the towline to measure towline tension for the purpose of obtaining early L/D information.

About 60 ground tows were made with each vehicle prior to the first air tows. The drag and speed range of the Paresev made it possible to use a wide variety of aircraft for air towing. In fact, the Paresev has been towed with an L-19, a Super-Cub, a 450 hp Stearman, and an HC-1A helicopter.

A limited number of tests were conducted to select a suitable air-tow vehicle for the M-2. The tests were made using a calibrated drag chute towed by a 450 hp Stearman and a C-47 which have acceptable operating velocities. The rate of climb available using the Stearman for tow was insufficient but was adequate when using the C-47. A World War II glider towhook was located for installation on the Flight Research Center C-47.

Because of the light wing loading of the towed craft, we were concerned with the possibility of the vehicles encountering tow-plane turbulence and becoming uncontrollable. To investigate this problem, several tows using a

Schweizer 1-26 sailplane were made to evaluate takeoff accelerations, acceptable tow positions, and towline lengths to insure minimum effects of tow-plane wake. The results of these tests indicated that a high tow position and the use of a 1,000-foot towline minimized the problem.

Before the first air tow, four rocket firings were made with the M-2--two static and two dynamic--to demonstrate structural integrity and the effect of propulsion on vehicle stability and control. The first dynamic firing was during a ground tow with nosewheel lift-off at about 60 KIAS. No pitch or yaw perturbations were noted by the pilot. Therefore, in a subsequent operation, a second firing was made after towline release at approximately a 10-foot altitude and 95 KIAS. Again, there was no adverse effect. In fact, the pilot reported some improvement in vehicle stability.

All of the air-tow tests were conducted in the early moring to take advantage of the calm air conditions. Initially, winds above a steady 5 knots would be cause for a flight cancellation. As pilot confidence increased, this requirement was relaxed until we were flying in gusting 10- to 15-knot winds with light turbulence (rated by a C-47).

A normal flight for either craft is a takeoff on the dry lakebed at Edwards Air Force Base and a circling flight path which skirts the lake edges to insure a landing on the lakebed in the event of a towline failure. Release altitude is normally 10,000 to 13,000 feet. Data are obtained during the glide. The last 2,000 feet of altitude are used by the pilot for maneuvering in preparation for the landing. The number of flights per day is usually limited only by the pilot's stamina or rough air conditions.

DATA MEASUREMENTS AND TECHNIQUES

The nature of the instrumentation installed in a vehicle and the data obtained are dependent, of course, on the objectives of the program. With the

Paresev, the primary objectives were to prove that the pilot could successfully execute a flared landing with the vehicle, and to obtain the basic performance characteristics of the vehicle. The objectives of the lifting-body program were more extensive, that is, to provide data useful for the design of a high-wing-loading vehicle, and to provide full-scale subsonic flight data of a general nature.

In the Paresev program, the general approach initially, for safety reasons, was to estimate the flare capability by using a simple longitudinal three-degree-of-freedom simulator. Performance characteristics, estimated from wing-alone wind-tunnel data, and approximate control characteristics were used to set up the analog program. Free-flight model tests and wind-tunnel tests indicated a longitudinal instability problem and a stick-force problem at low angle of attack that could not be simulated. This area, however, was avoided in flight tests. From the results of the simulator program, it was concluded that a flare could be accomplished with the vehicle.

Lateral-directional analytical studies were not accomplished before the vehicle was flown, for two reasons. First, sufficient data did not exist to accomplish such a study; second, free-flight model tests conducted by the NASA Langley Research Center indicated that the lateral-directional characteristics would not be a problem area.

The first data obtained in the Paresev program were Fairchild theodolite photographs of free flights initiated at approximately 150-foot altitudes. From these photographs, range, altitude, pitch attitude, and time were measured directly, and the parameters shown in figure 9 were derived. From several flights of this type the flare capability was evaluated, and a reasonable estimate of the performance was made. This approach, combined with pilot comments, was considered a satisfactory method to answer the question about flare capability, but was not considered precise enough for accurate measurement of vehicle performance.

The performance characteristics were obtained in a very simple manner by flying at constant airspeed, which the pilot noted, and recording elapsed time, with a stop-watch, to descend a given altitude increment. With appropriate corrections for airspeed errors and density altitude, airspeed and rate of descent corrected to sea-level conditions were obtained. Then, using the relationship shown in figure 10, the performance characteristics C_D and L/D vs C_L were derived. The large discrepancy between flight and predicted values of C_D and L/D was due primarily to improved sail contouring and overcompensation for some additional structure. This method was considered satisfactory, with errors estimated not to exceed 5 percent. However, for vehicles operating at higher speeds and rates of descent, errors due to timing lag, altitude lag, and other errors in the pressure-sensing systems become appreciable.

With the above-described techniques, the data necessary to accomplish the initial program objectives were obtained. A complete instrumentation system is currently being installed in the Paresev to obtain stability and control data to supplement the initial qualitative evaluation.

An instrumentation system sufficiently complete to obtain both stability and performance data from onboard instruments was installed in the lifting body.

The first item to be investigated in the flight-test program was, of course, flare capability. From instantaneous changes in angle of attack at touchdown and from Askania tracking data, the touchdown vertical velocity has been determined to be less than 5 ft/sec, thus proving the capability of the pilot and vehicle to execute a flare maneuver.

Since several methods of determining performance characteristics were available, a fairly complete analysis was made to determine the best method. Askania tracking was not used because it is sensitive to changing wind conditions. The technique used in the Paresev tests was not employed because of the errors resulting from altitude and airspeed lags at the high rates of descent encountered with the lifting body. The method used was to determine normal and longitudinal acceleration at a specific angle of attack. Then, using the axis transfer equation shown in figure 11, the lift-drag ratio versus angle-of-attack data shown in the figure were determined. The primary advantage of this method is that it is most sensitive to the most accurately measured parameters, a_z and a_x, and least sensitive to the less accurately measured parameter, α. An additional advantage is that lift-drag-ratio data may be obtained during maneuvering flight, thus, many data points may be obtained on each flight.

Currently, stability derivatives are being determined from flight pulse maneuvers, using the analog-matching technique for analysis of flight data. A mechanical stick-fixing device is employed during the flight tests to insure data without any control inputs. To date, sufficient data have not been analyzed for presentation.

LIFTING-BODY ANALYSES

Prior to flight test of the lifting body, the Flight Research Center conducted several analytical studies to determine that the vehicle was safe to fly. These studies fell into two broad catagories: flare and landing, and stability and control.

Because of the low predicted maximum lift-drag ratio, landing was considered a major problem area. Hence, the flare and landing were carefully investigated using both IBM and analog techniques. From Paresev flight tests (fig. 9), it was determined that $\dot{\alpha}$ approximately constant during the flare was a reasonable approximation to an actual flare. Using this α input to the rigid-body longitudinal equations of motion, the results shown in figure 12 were obtained. These results show that if the pilot flies to the right of the $\dot{h} = 0$ line, he will have excess energy to flare, that is, coasting time after flare completion. Lifting-body flight data (fig. 13) show that $\dot{\alpha}$ approximately constant during the flare is a reasonable approximation to the actual flare maneuver, thus verifying the initial approximation.

The flare problem was also studied on a three-degree-of-freedom analog simulator to develop piloting techniques and determine visibility requirements. A cardboard mockup providing the visibility available in the flight vehicle was made and used in conjunction with a rudimentary visual shadowgraph presentation. This simulation complemented the IBM program in determining velocities and flare-initiation altitudes for unpowered landings. In addition, the sizing of the landing-assist rocket was accomplished on this simulator by setting up abnormal conditions at flare altitudes and determining the thrust necessary for correction back to normal flare condition at some time prior to touchdown.

The second area, lateral-directional stability and control, was investigated using both an analog simulator and root-locus analytical methods. As will be related below, several difficulties were encountered in this area because of the misinterpretation of the results and wind-tunnel data that did not agree closely with flight results.

The first control configuration considered was a standard arrangement, with the stick linked to the elevons and flaps (differential) and the rudder pedals linked to the rudders. For this configuration, the simulators showed a slow lateral response due to a low value of L_{δ_a}. The root locus showed that the control technique of $\delta_a \sim \varphi$ was more stable than $\delta_r \sim \varphi$, but did not give a good evaluation of the relative control effectiveness. The root locus and roll-controllability parameters $\left(N_\beta - L_\beta \frac{N_{\delta_a}}{L_{\delta_a}}\right)$ indicated that a roll reversal existed for $\delta_r \sim \varphi$. The simulator, however, did not indicate that this would be a problem area. Then, based on the above considerations, it was decided to use the rudders as the primary lateral control, with the rudders linked to the stick and the elevons, and flaps (differential) linked to the rudder pedals.

Short-duration flights, 0.5 second, indicated major differences between how the M-2 felt in flight and in the simulator. The simulator was then carefully checked, using the critical gain computed from the root locus. This simulation checked out very well, thus still not solving the problem. At this point, a flight time history was obtained from the motion-picture film, and an analog match was attempted. It was found that the motions could not be matched unless L_{δ_a} was increased by a factor of four. On the basis of this increased elevon effectiveness, the controls were again rerigged in a normal manner with the stick linked to the elevons only, to decrease N_{δ_a}, and the rudder pedals linked to the rudders. This system worked fine, but the improvement was partially obscured by the presence of the large center fin. After two ground tows, the center fin was removed and the subsequent ground tow resulted in a long, smooth flight.

This latest configuration worked well and has been retained for the flight research program. Approximately 140 ground-tow flights and 16 air-tow flights have been made with no problems.

GENERAL COMMENTS

We have alluded in general terms to the low costs and times to the first flight of these programs. Now, we shall be more specific.

The total cost for construction and 1 year of operation for the Paresev was $30,000. During this time, 7 pilots were checked out in the vehicle. This includes a total of approximately 200 ground tows and 70 air tows, and 1 major and 4 minor repair jobs. From the time of program conception to the first flight required about 8 weeks.

The total cost for construction and operation through the first 10 air tows of the M-2 was $60,000 and covered a period of 9 months. This includes about 80 ground-towed flights. From the time of program "go-ahead" to the first ground tow was about 4 1/2 months. At the present time we are in the process of checking out three new pilots in the M-2 in order to have a broader evaluation of the craft.

We feel that our program approach has been successfully demonstrated in that we have investigated these configurations and obtained flight data on them. Over 400 successful ground- and air-towed flights have been made and 10 pilots have flown the craft without serious incident.

CONCLUDING REMARKS

From the Paresev and lifting-body programs the following conclusions have been reached:

1. These two programs have shown that manned, conceptual flight testing can be conducted safely, economically, and expediently. To accomplish this, it is often necessary to simplify the organization of routine office and shop paper-work.

2. In order to cut costs and fabrication time, use of experienced craftsmen in allied fields should be considered. Such capability is often found in relatively small shops.

3. Flight data and piloting experience obtained with these types of vehicles add to the general knowledge of aerodynamics and the understanding of simulator work and help to substantiate the predictions for heavyweight versions.

4. Analog simulations are useful for developing piloting techniques and, combined with the shadowgraph, are very useful for developing visibility requirements.

5. The root-locus technique and analog simulations are essential analytical tools for estimating stability and control characteristics prior to flight testing; however, the limitations must be recognized, and care must be used in

the interpretation of the results of both methods.

6. Finally, and certainly not the least important, are the intangible results from this type of research, which are the enthusiasm and interest that it develops within NASA, industry, and the military.

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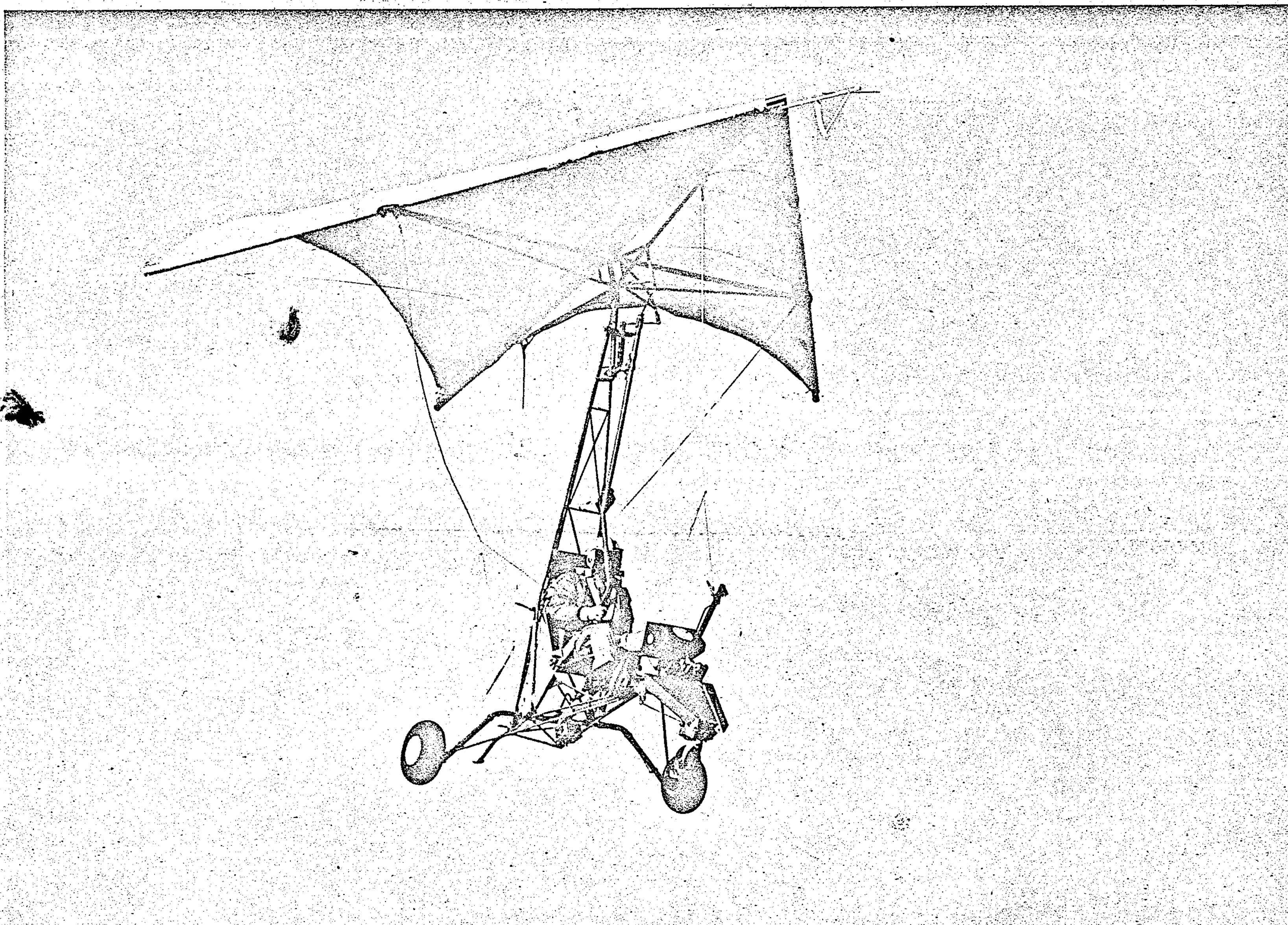

Figure 1.- Vehicle A in flight.

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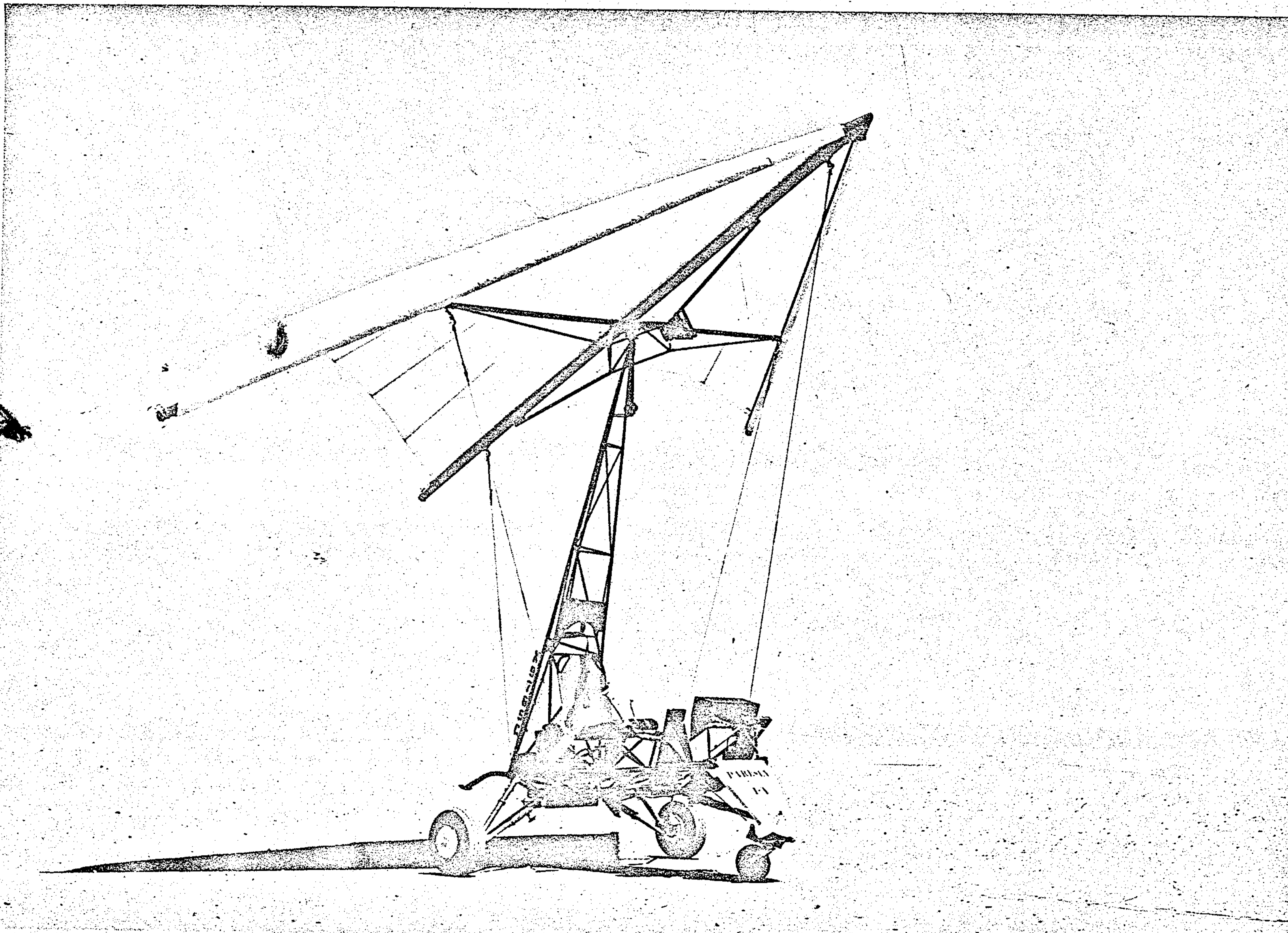


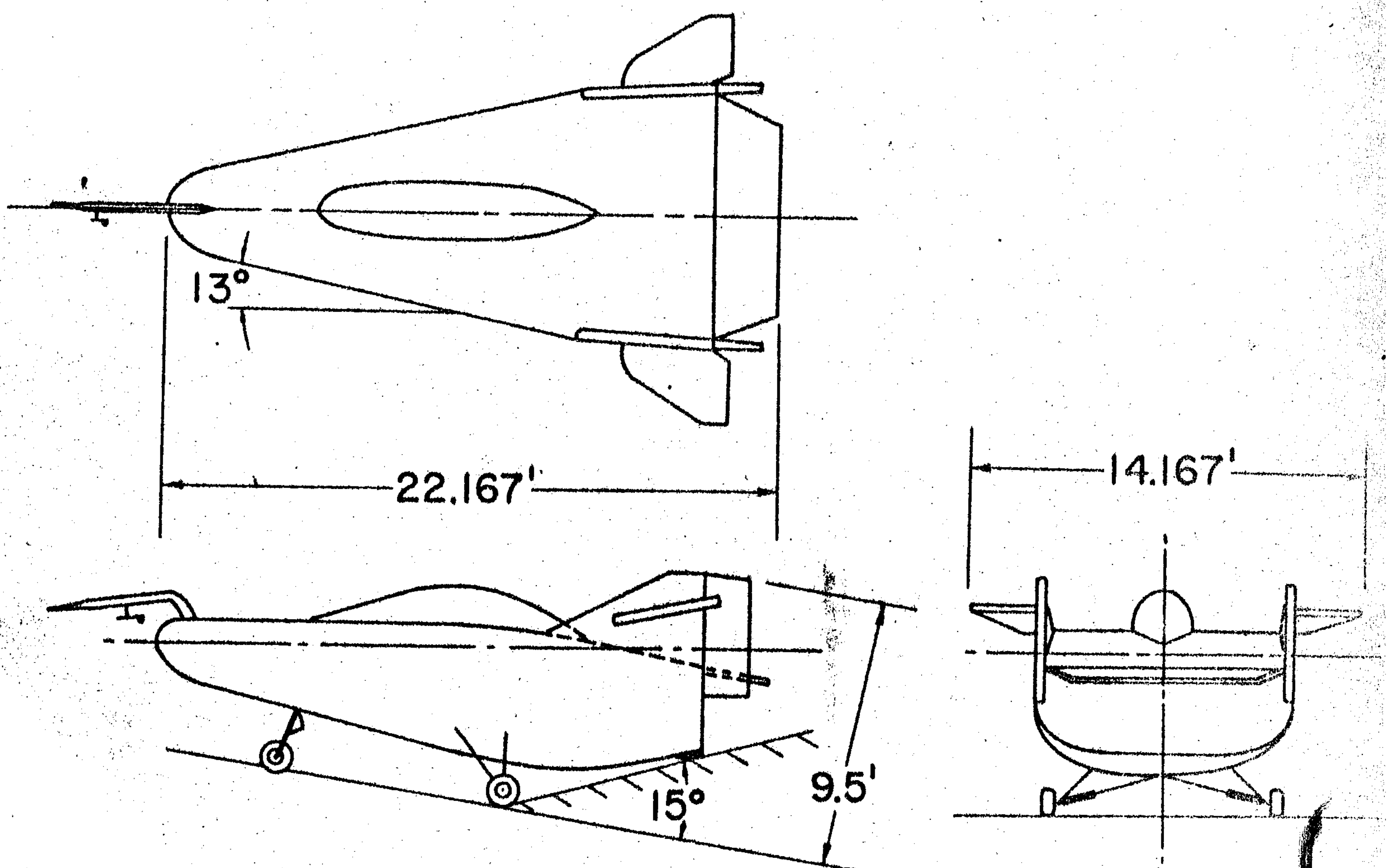
Figure 2.- Vehicle B.

COMPARISON OF VEHICLE CHARACTERISTICS

Component	Vehicle A	Vehicle B
Fuselage	Main longitudinal member was single 1 1/2-inch-diameter tube	Built-up truss instead of single tube
Control system	Direct link	Cable-operated
Wing membrane	Doped Irish linen	6-ounce unsealed Dacron
Main landing gear	Single steel tube	Shocks and bungees used

Figure 3

VEHICLE CHARACTERISTICS



HALF CONE (26° INCLUDED ANGLE)

WING AREA – 139 SQ FT

VOLUME – 464 CU FT (HULL ONLY)

WEIGHT – 1180 LB (TOTAL)

TOTAL EXTERNAL-SURFACE AREA
EXCLUDING BASE – 450 SQ FT

WING LOADING – 8.49 PSF

Figure 4

1536

HULL ASSEMBLY

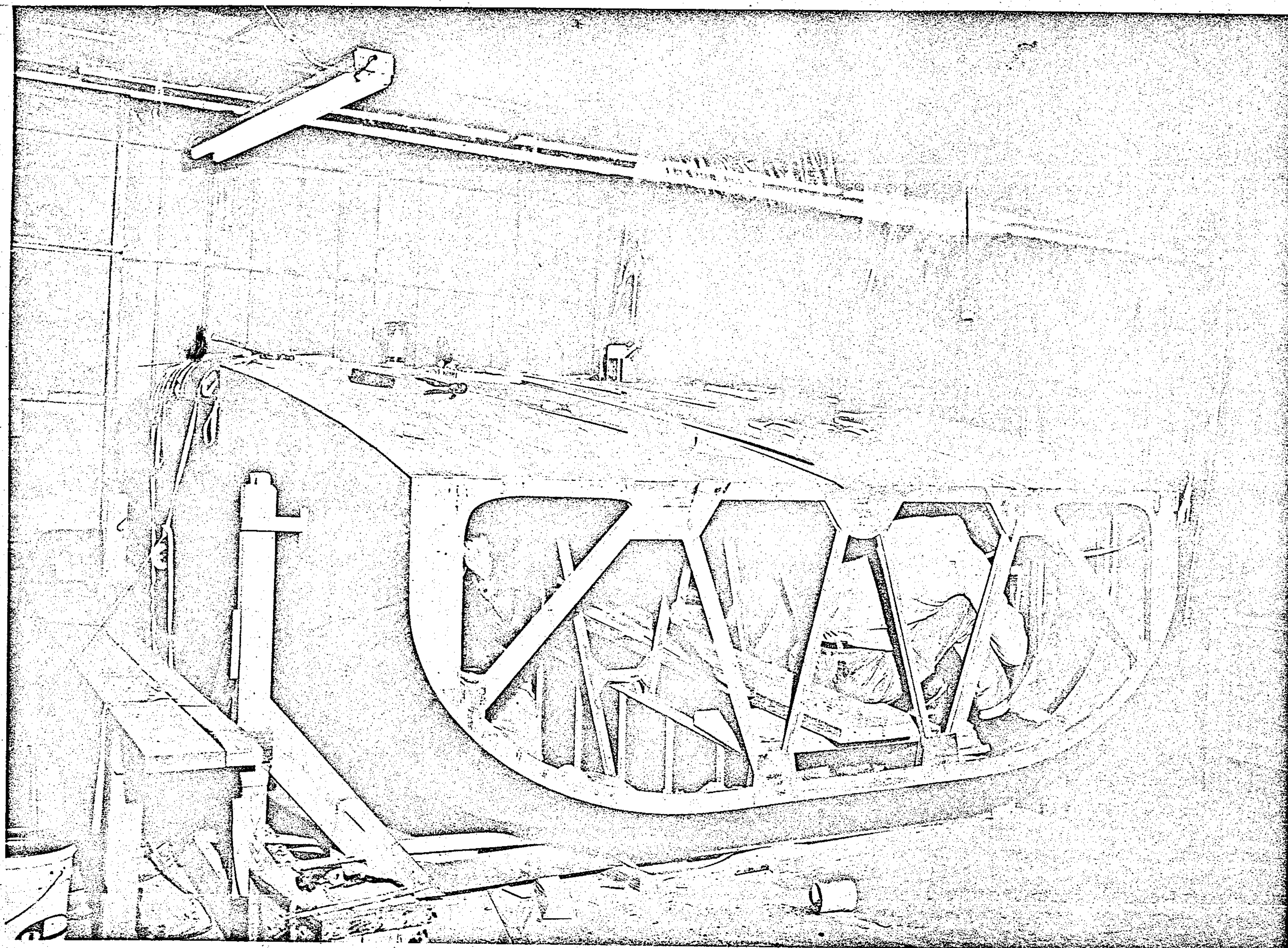


Figure 5

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INTERNAL STRUCTURE

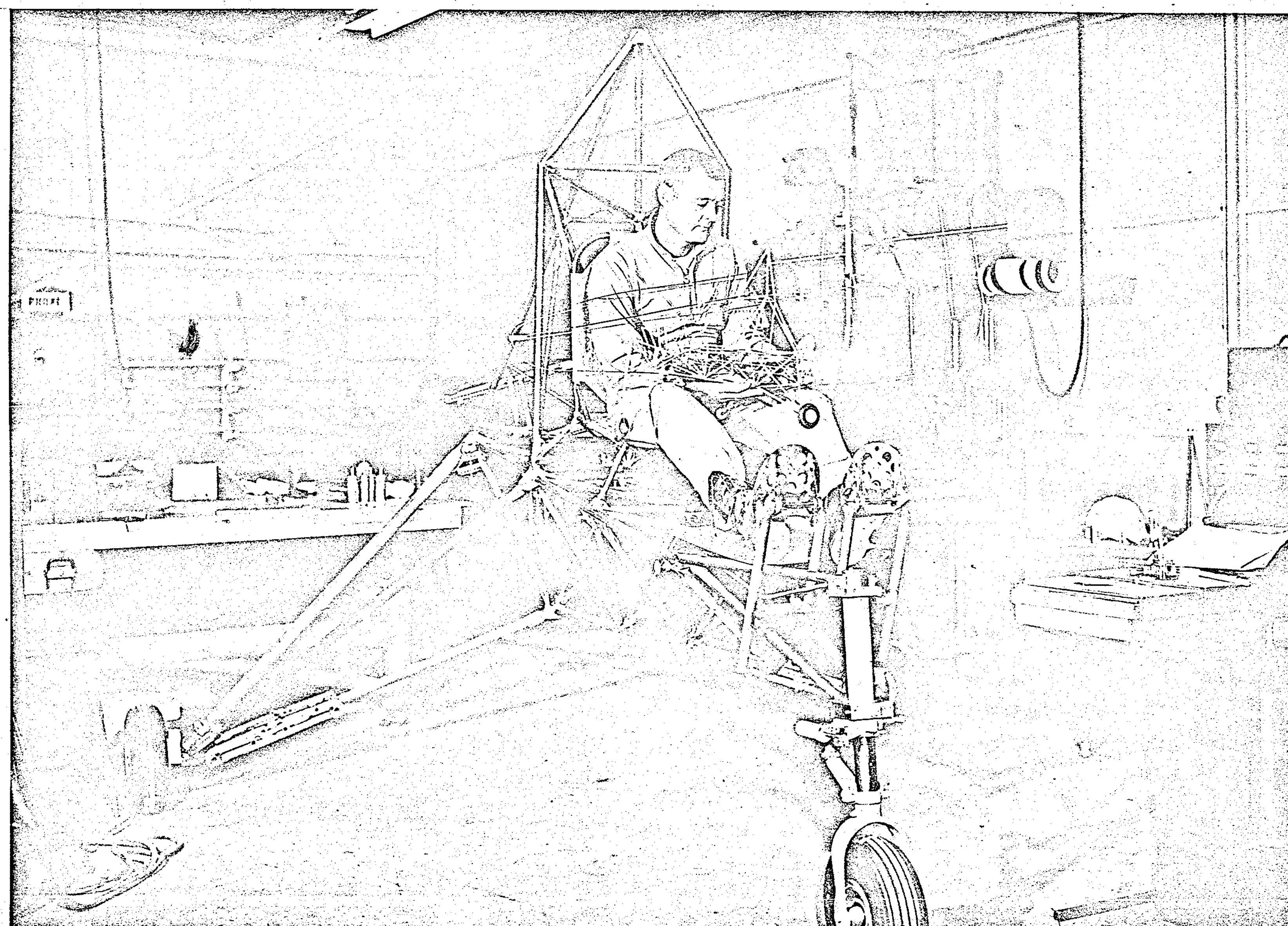

Figure 6

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M-2 VEHICLE

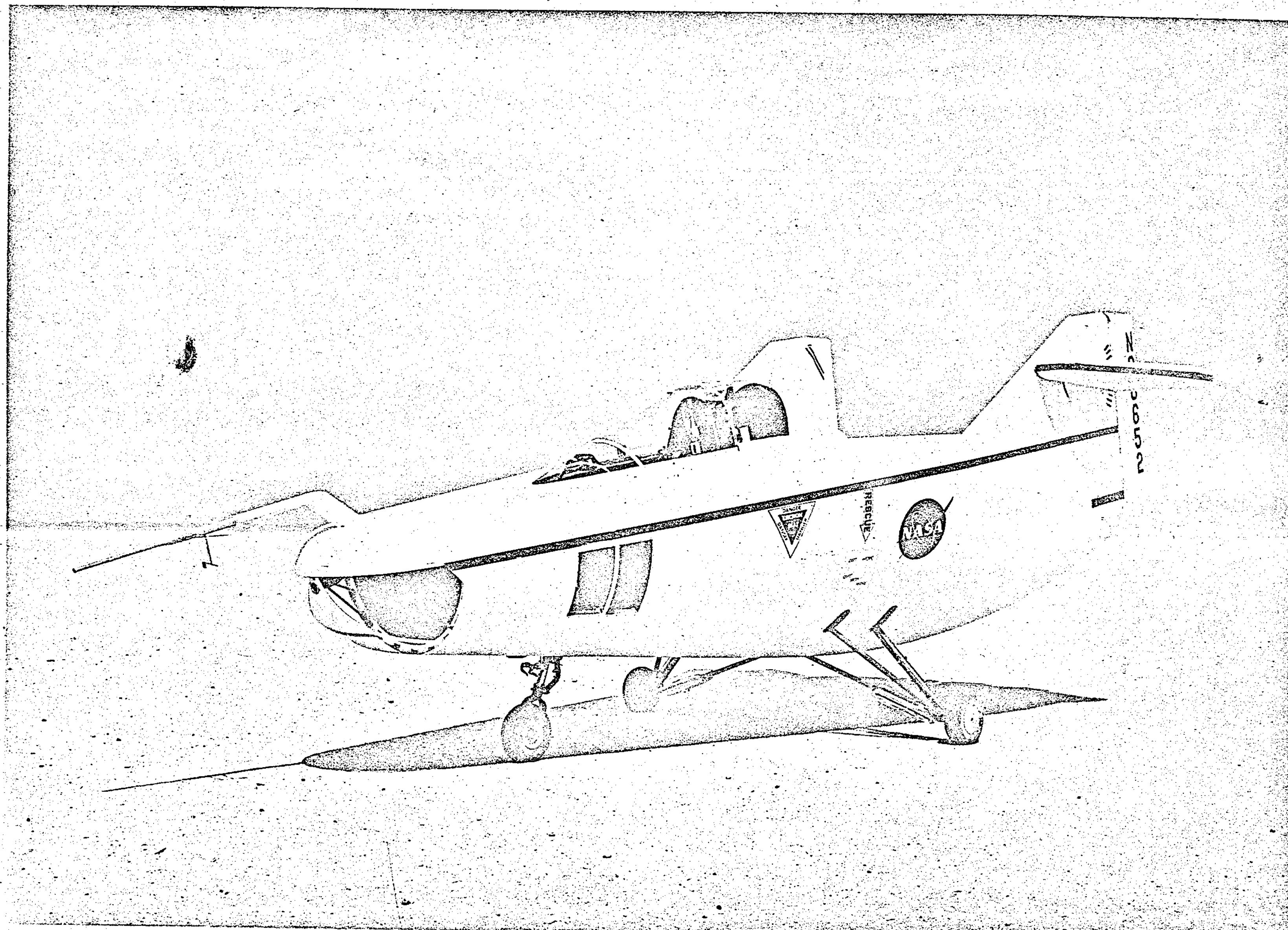


Figure 7

FULL-SCALE TUNNEL TESTS OF FLIGHT VEHICLE

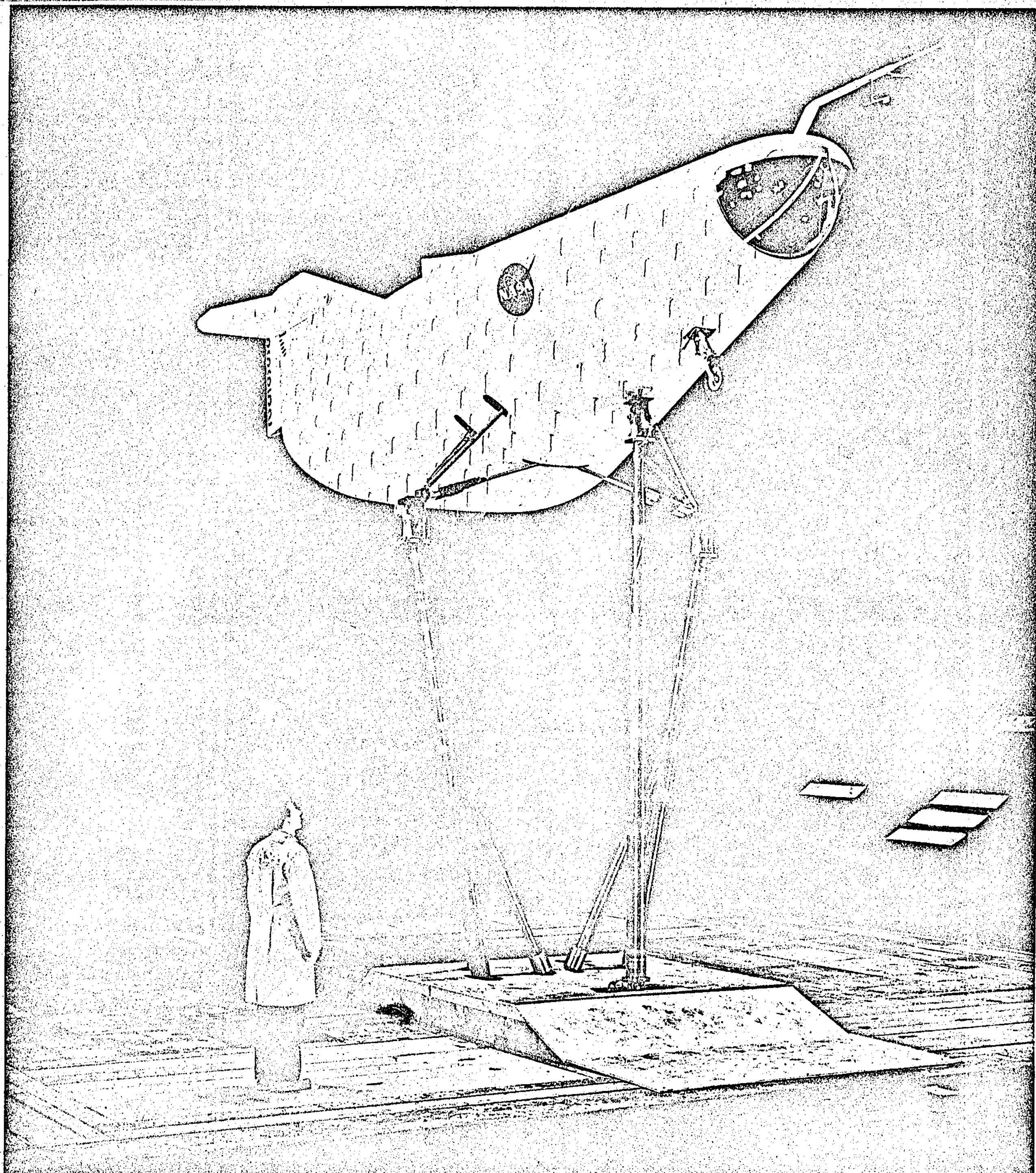
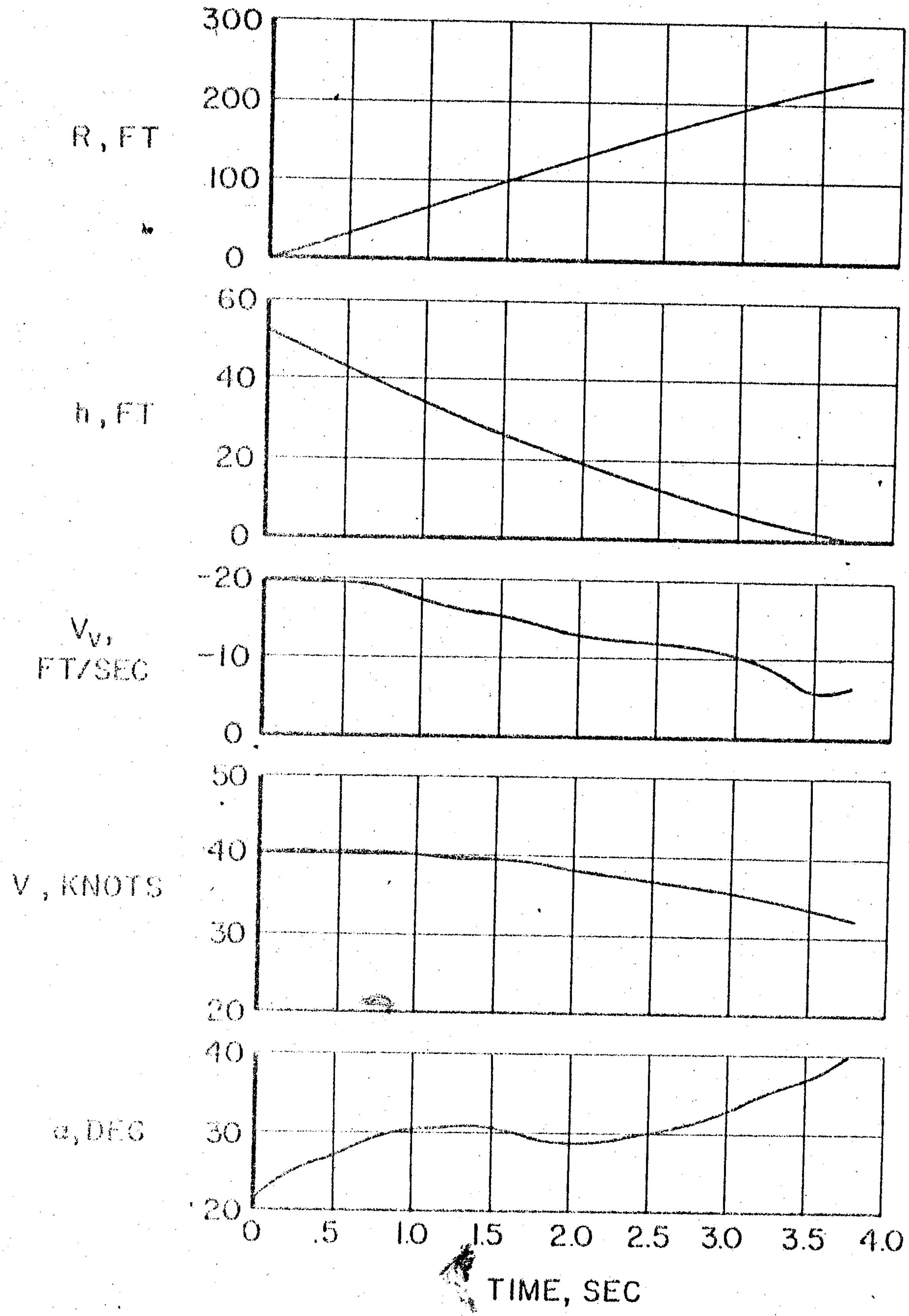


Figure 8

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

PARESEV LANDING TIME HISTORY



PARESEV PERFORMANCE CHARACTERISTICS

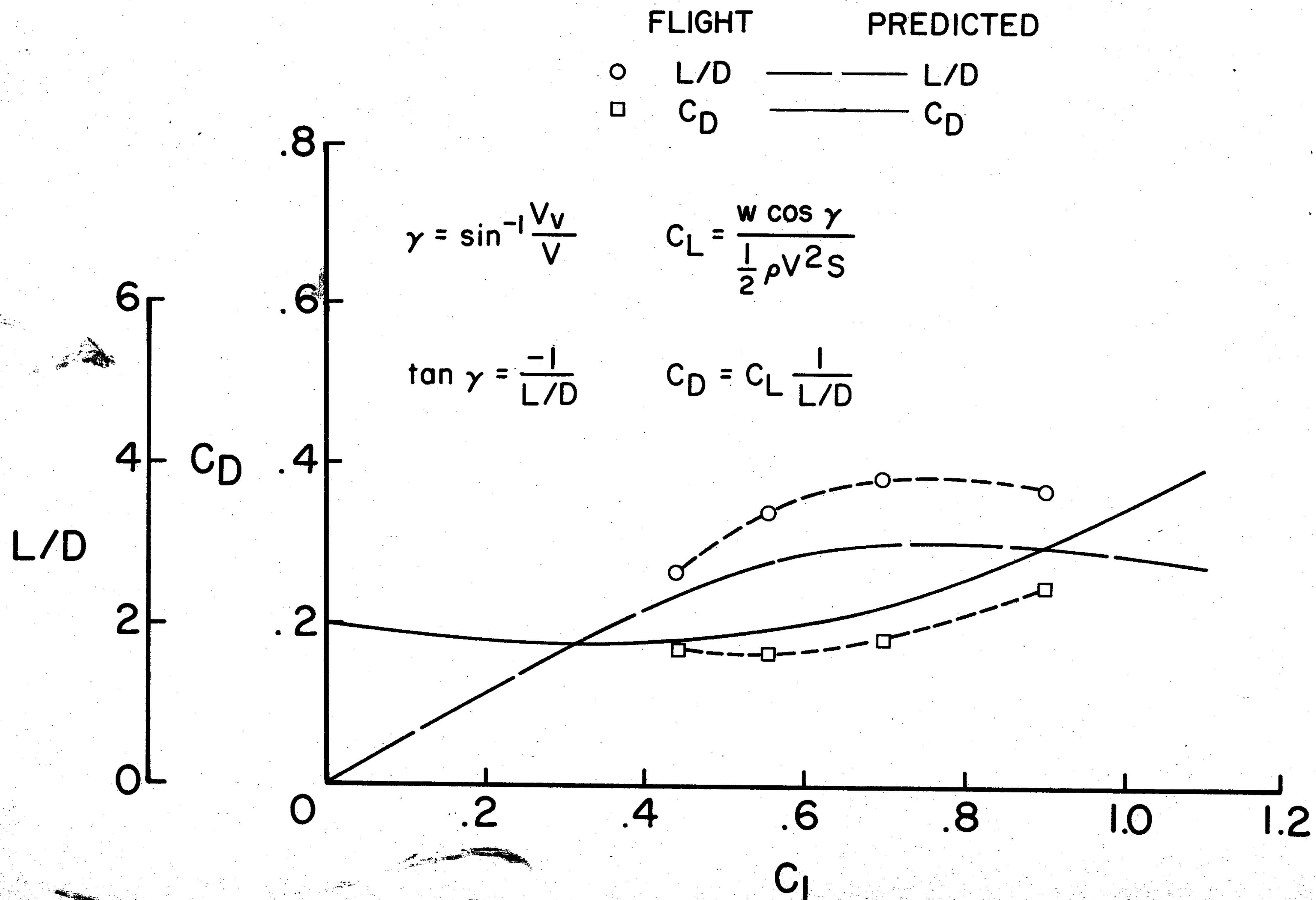


Figure 10

VARIATION OF LIFT-DRAG RATIO WITH ANGLE OF ATTACK FOR M-2 LIFTING BODY

$$L/D = \frac{A_Z \cos\alpha + A_X \sin\alpha}{A_Z \sin\alpha - A_X \cos\alpha}$$

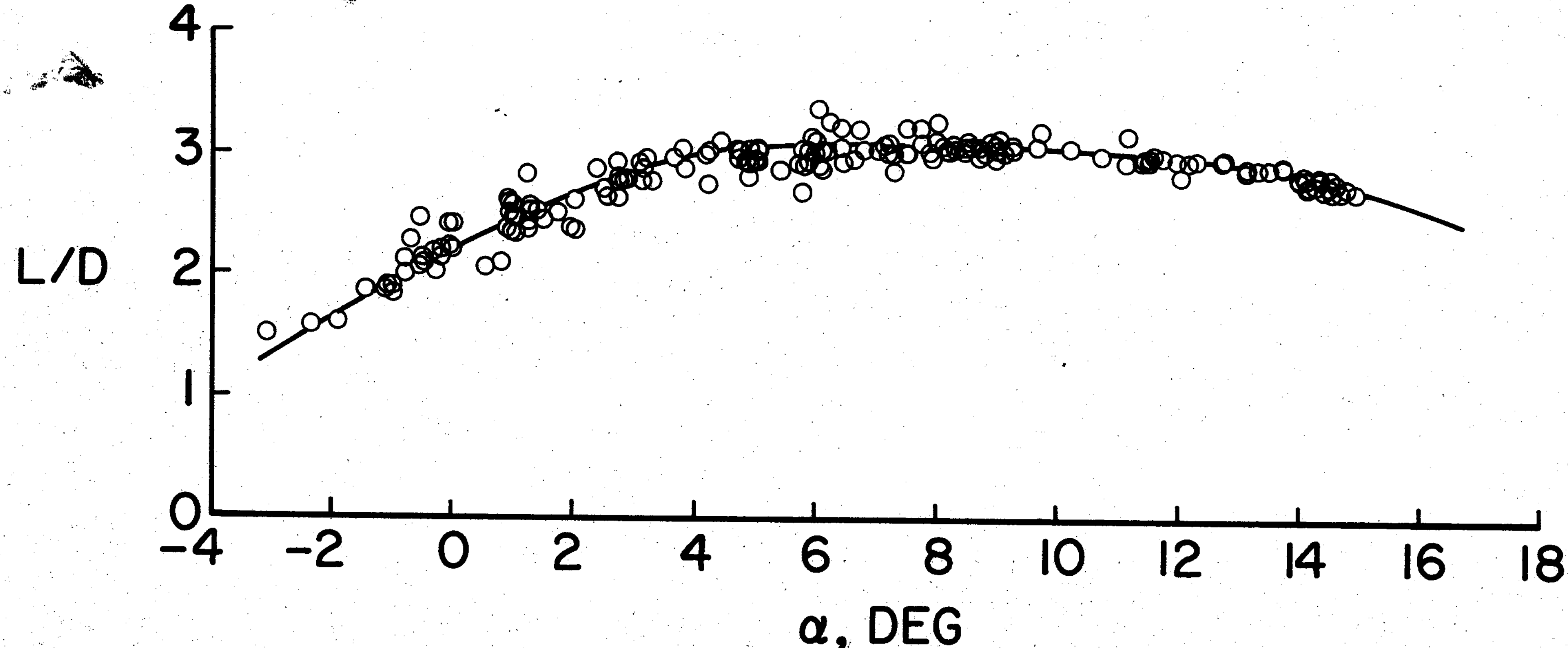


Figure 11

LIFTING BODY $\dot{\alpha}$ DURING FLARE VS. VELOCITY PRIOR TO FLARE

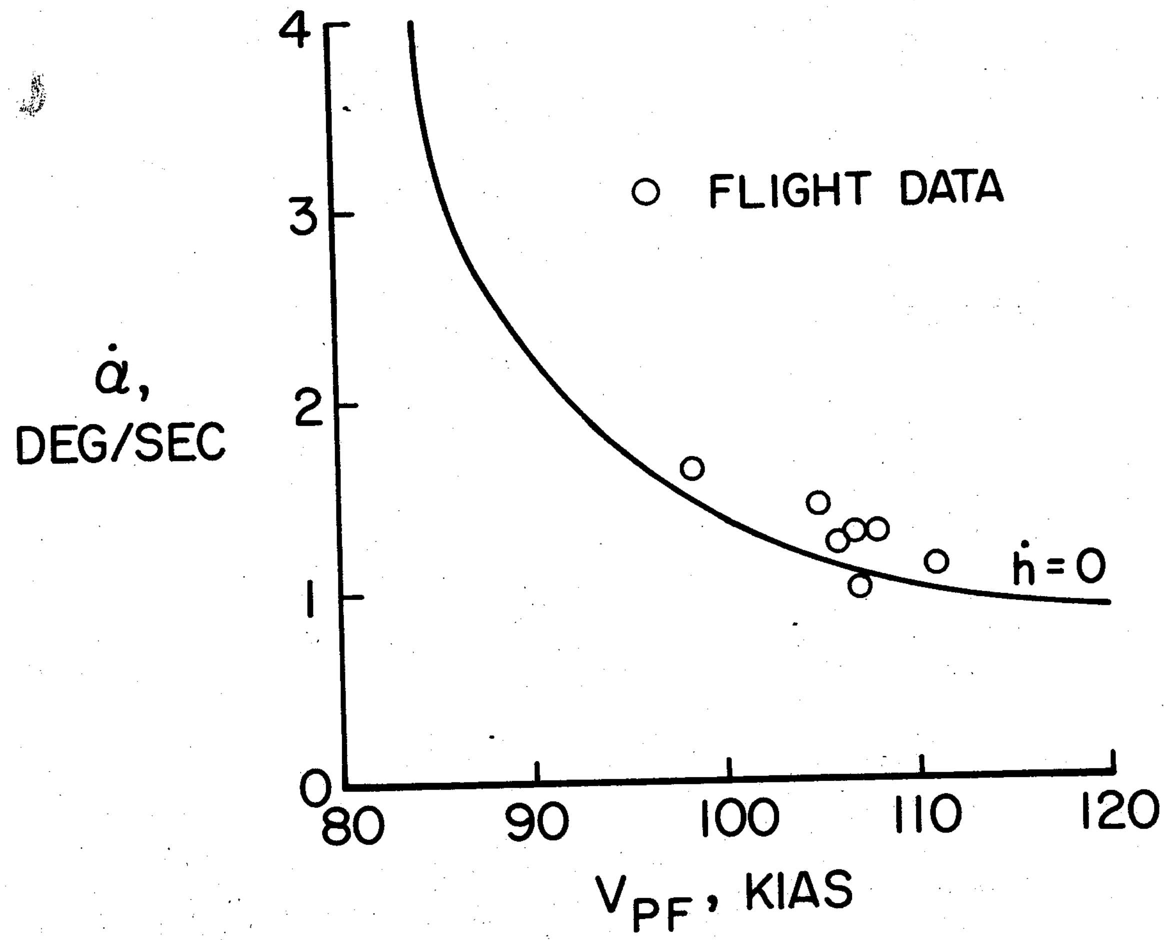


Figure 12

LIFTING BODY TYPICAL α TIME HISTORY DURING FLARE

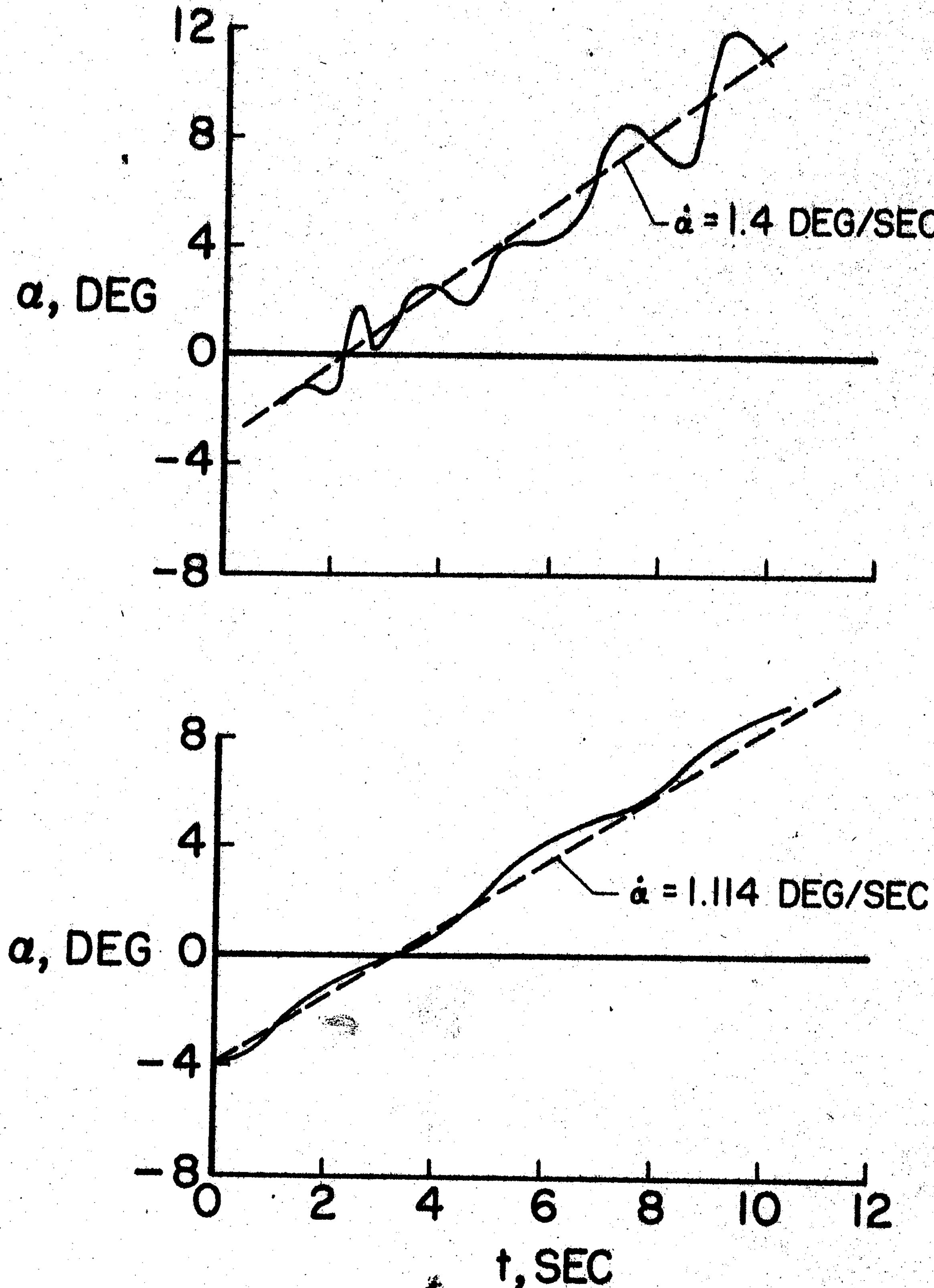


Figure 13